Non-Linear Shaping BPF-based Oscillator with Enhanced Linearity

Oct. 2008

Prepared by

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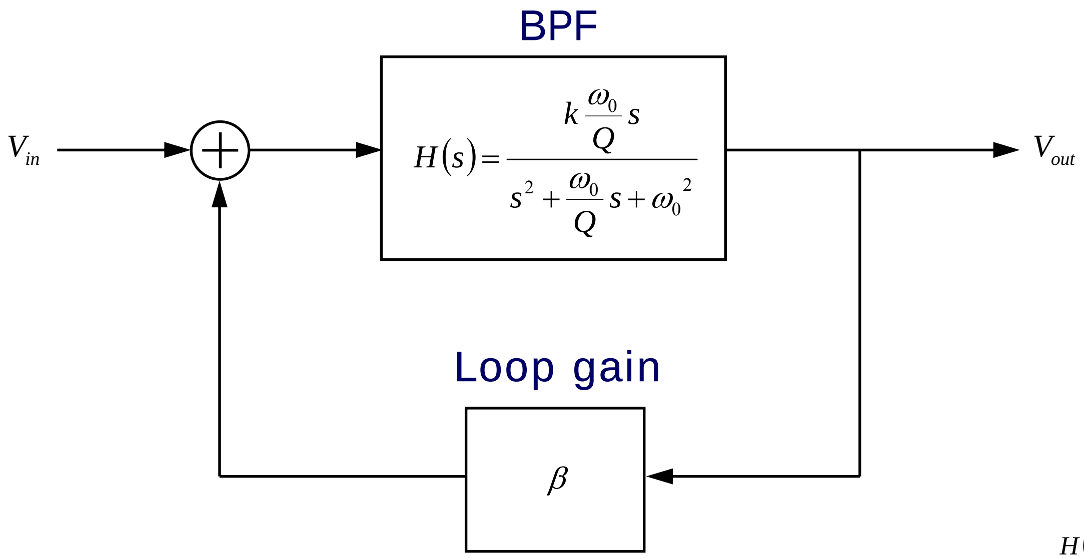
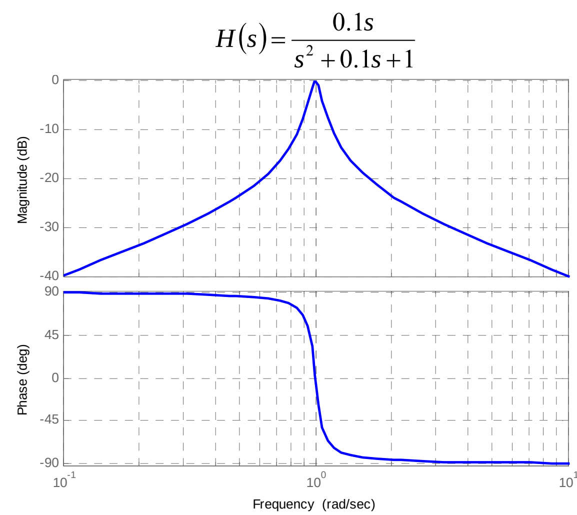
❑ BPF-based oscillator



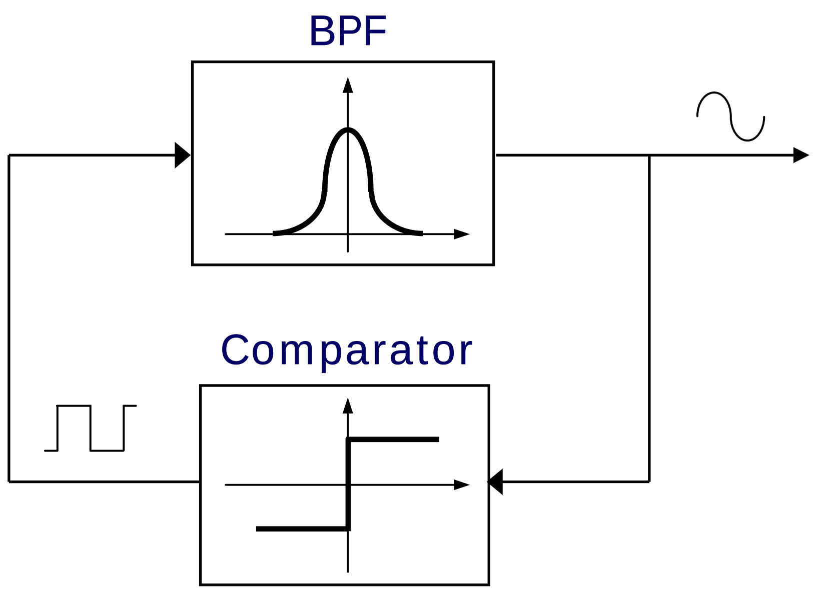


- BPF : Gain (*k* at ω=ω$_0$), Phase (*0* at ω=ω$_0$)

- $$\frac{V_{out}(s)}{V_{in}(s)}=\frac{H(s)}{1-\beta H(s)}=\frac{k\dfrac{\omega_0}{Q}s}{s^2+\dfrac{\omega_0}{Q}(1-\beta k)s+\omega_0^2}$$

- Oscillation condition $\beta \geq \dfrac{1}{k}$

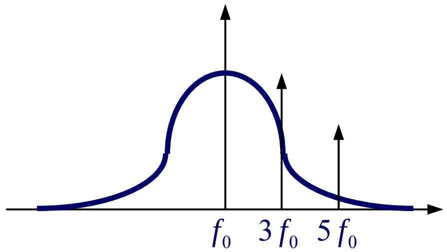
❑ BPF-based oscillator



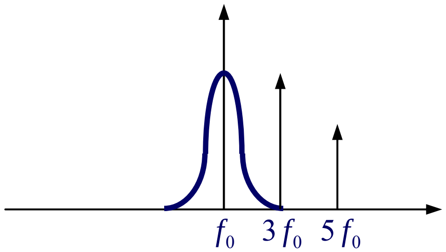
- **Comparator** is conventionally used in the loop
- Large gain enough for oscillation
- Saturate output for oscillation amplitude
- What about linearity?

❑ Q-factor of BPF on Linearity

Low-Q BPF



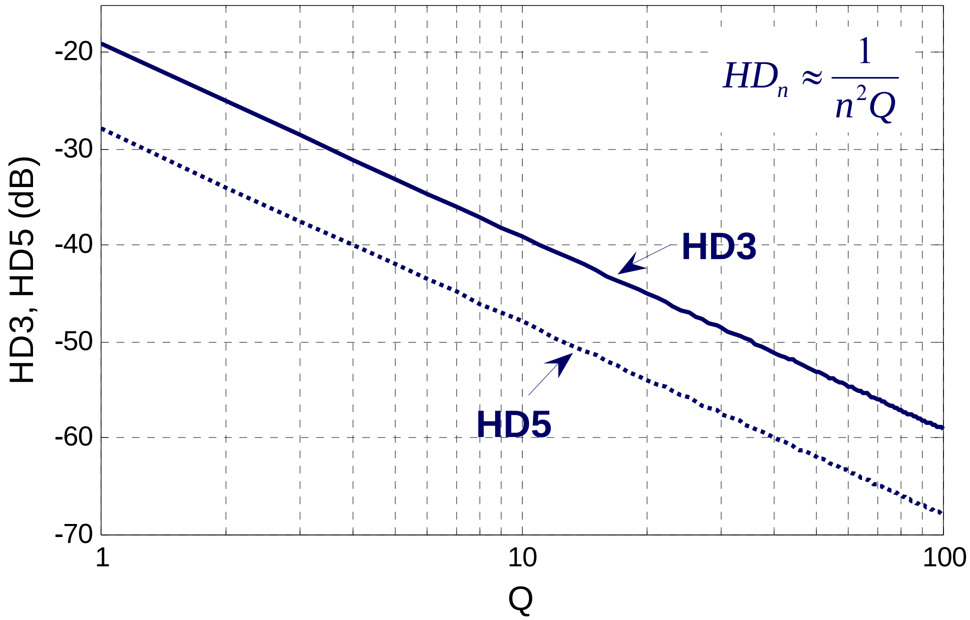
High-Q BPF



- Input of BPF is roughly a square wave
- Most significant harmonics are 3rd and 5th order
- Requires very high Q-factor for low distortion

  (i.e. Q = 35 is required for HD3 = -50 dB)

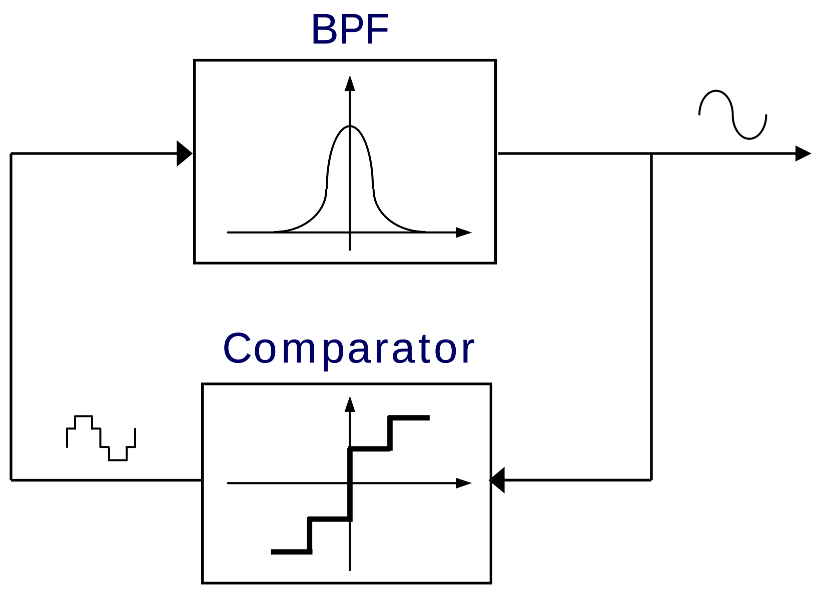
❑ Q-factor of BPF on Linearity



➢ More than 100 of Q-factor is required for HD3 = -60dB

- Not practical

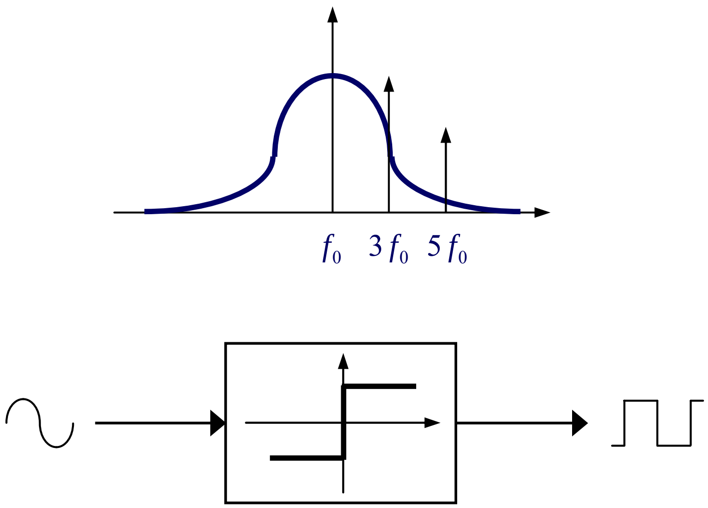
❑ BPF-based Oscillator with Multi-level Comparator



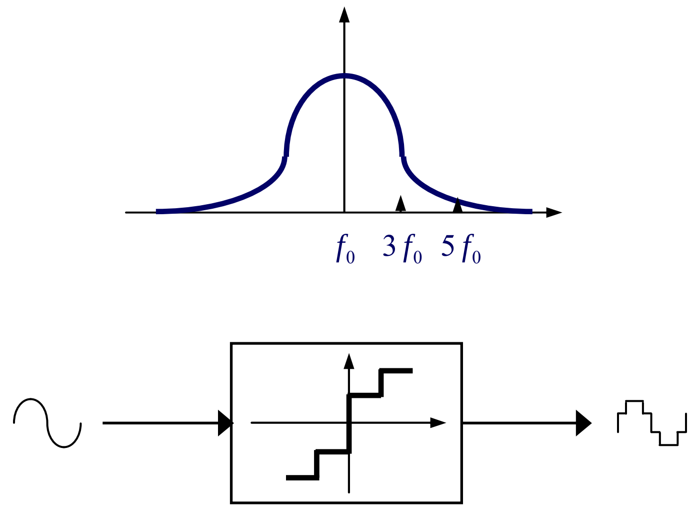
- Multilevel comparator optimized for harmonic rejection
- BPF Q-factor requirement is relaxed

❑ Harmonic Rejection with Multilevel Comparator

Conventional Comparator

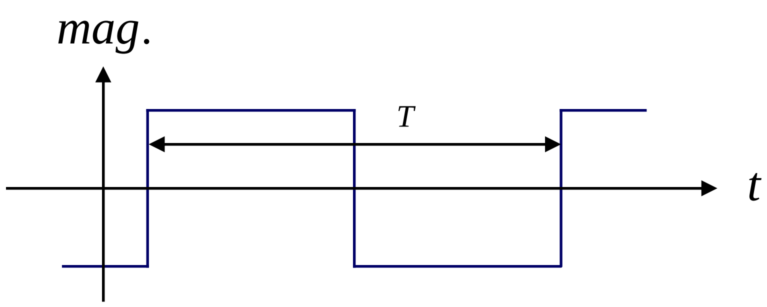


Multi-level Comparator

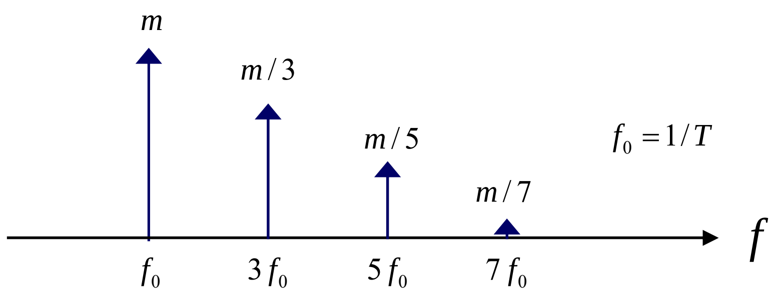


- 3rd and 5th harmonics are rejected by multilevel comparator
- High linearity can be achieved without high-Q BPF

❑ Two-level Square Wave



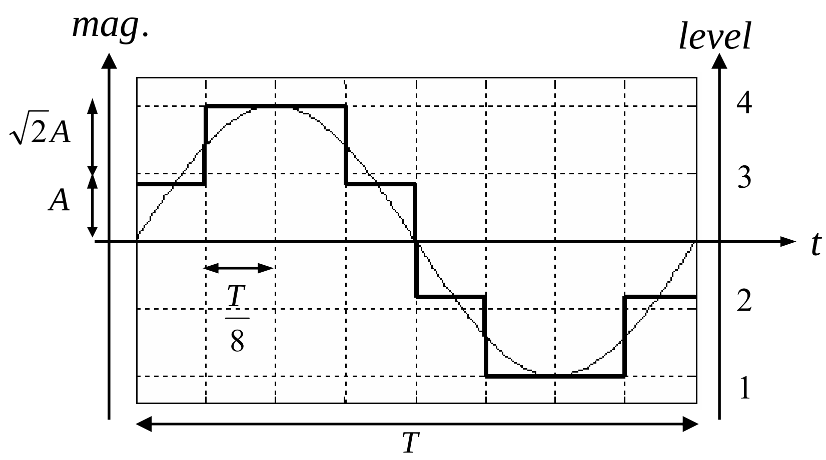
Time domain

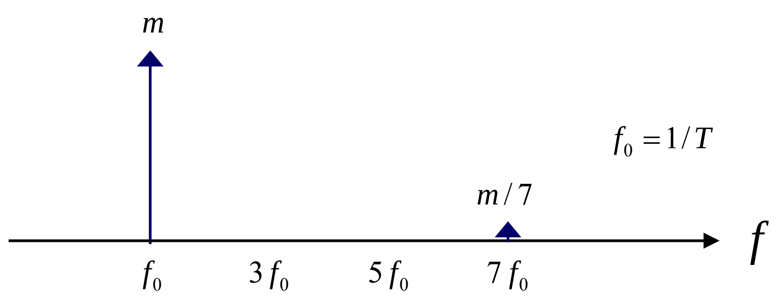


Frequency domain

- Common signal source
- Easy to implement
- Odd harmonics and no even harmonics due to symmetric property
- Most significant harmonics : 3rd and 5th order

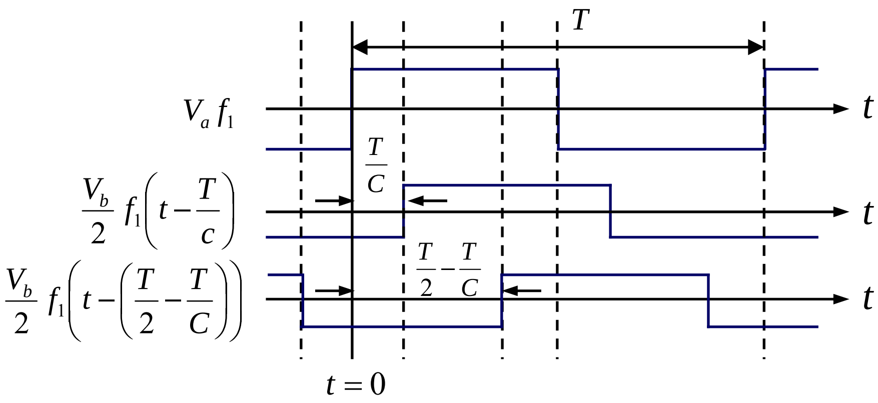
❑ Multi-level Square Wave

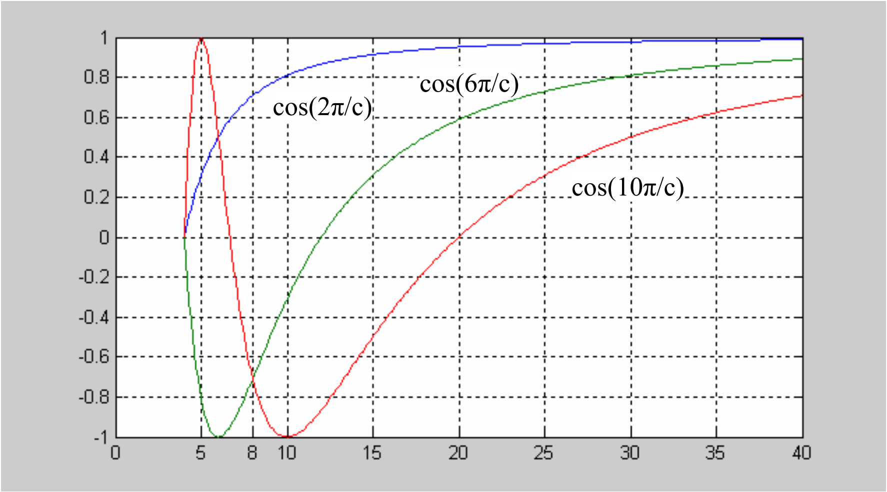




- Signals
  - Magnitudes = $1 \quad 1/\sqrt{2}$
  - Phase shifts = $\angle 0^\circ \quad \angle \pm 45^\circ$
- Selectively rejects 3rd and 5th harmonics

❑ Multi-level Square Wave





$$F(\omega)=V_aF_1(\omega)+\frac{V_b}{2}e^{-j\omega\frac{T}{c}}F_1(\omega)-\frac{V_b}{2}e^{-j\omega\left(\frac{T}{2}-\frac{T}{c}\right)}F_1(\omega)$$

$$=\left\{V_a+\frac{V_b}{2}\left[\cos\left(\frac{T}{c}\omega\right)-\cos\left(\left(\frac{T}{2}-\frac{T}{c}\right)\omega\right)\right]\right\}F_1(\omega)$$

$$=\left\{V_a+V_b\cos\left(\frac{T}{c}\omega\right)\right\}F_1(\omega)$$

$$F(\omega_0)=\left\{V_a+V_b\cos\left(\frac{2\pi}{c}\right)\right\}F_1(\omega_0)$$

$$F(3\omega_0)=\left\{V_a+V_b\cos\left(\frac{6\pi}{c}\right)\right\}F_1(3\omega_0)$$

$$F(5\omega_0)=\left\{V_a+V_b\cos\left(\frac{10\pi}{c}\right)\right\}F_1(5\omega_0)$$

for $c=8$,

$$F(\omega_0)=\left\{V_a+\frac{V_b}{\sqrt{2}}\right\}F_1(\omega_0)$$

$$F(3\omega_0)=\left\{V_a-\frac{V_b}{\sqrt{2}}\right\}F_1(3\omega_0)\qquad F(5\omega_0)=\left\{V_a-\frac{V_b}{\sqrt{2}}\right\}F_1(5\omega_0)$$

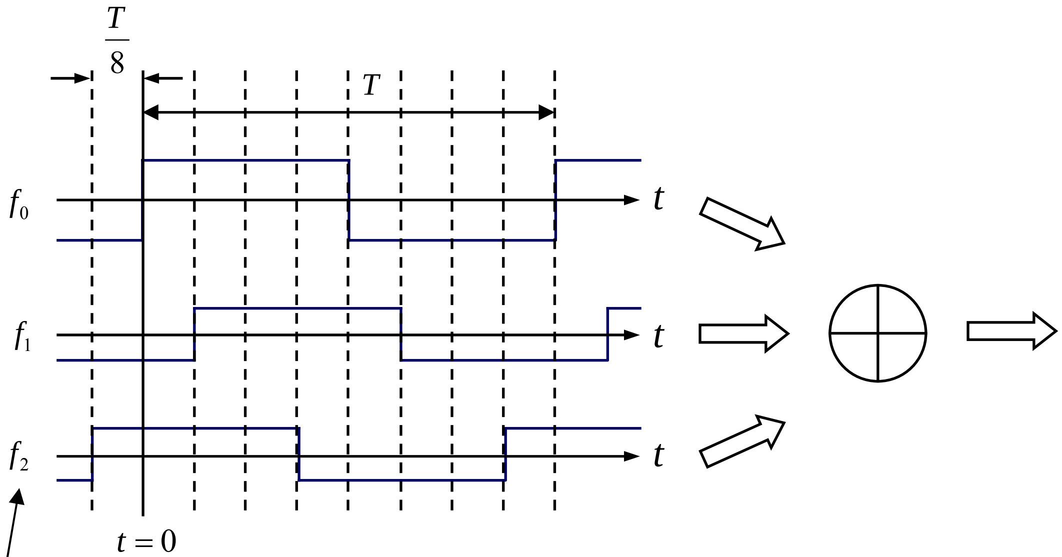
for $V_b=\sqrt{2}V_a$

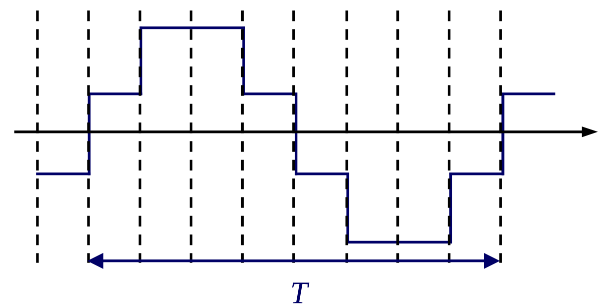
$$F(\omega_0)=2F_1(\omega_0),\quad F(3\omega_0)=F(5\omega_0)=0$$

❑ Multi-level Square Wave

$$f(t) = f_0(t) + \frac{1}{\sqrt{2}} f_0\left(t - \frac{T}{8}\right) + \frac{1}{\sqrt{2}} f_0\left(t + \frac{T}{8}\right)$$

$$F(\omega) = F_0(\omega)\left(1 + \frac{1}{\sqrt{2}} e^{-j\omega\frac{T}{8}} + \frac{1}{\sqrt{2}} e^{+j\omega\frac{T}{8}}\right)$$





$$-f\left(t - \left(\frac{T}{2} - \frac{T}{C}\right)\right) = f\left(t + \frac{T}{C}\right)$$

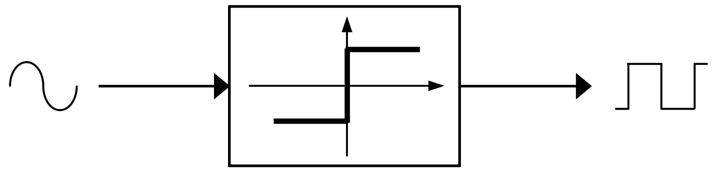
$$F(\omega_0) = F_0(\omega_0)\left(1 + \sqrt{2}\cos\left(\frac{\pi}{4}\right)\right) = 2F_0(\omega_0)$$

$$F(7\omega_0) = F_0(7\omega_0)\left(1 + \sqrt{2}\cos\left(\frac{7\pi}{4}\right)\right) = 2F_0(7\omega_0)$$

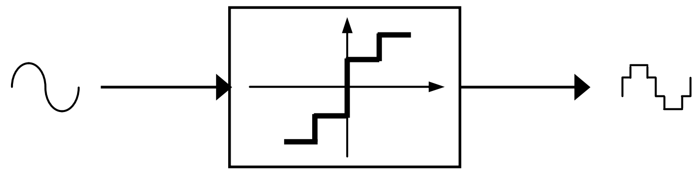
$$F(3\omega_0) = F_0(3\omega_0)\left(1 + \sqrt{2}\cos\left(\frac{3\pi}{4}\right)\right) = 0$$

$$F(5\omega_0) = F_0(5\omega_0)\left(1 + \sqrt{2}\cos\left(\frac{5\pi}{4}\right)\right) = 0$$

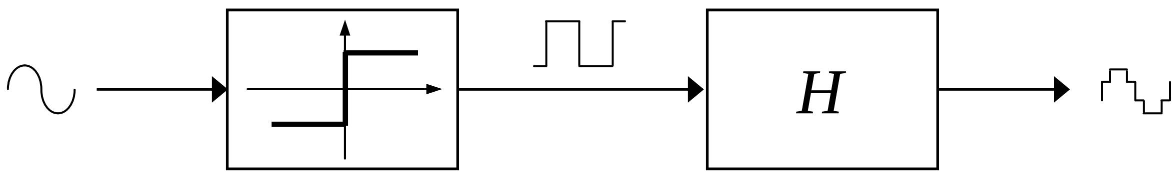
❑ Comparators



➢ Conventional comparator

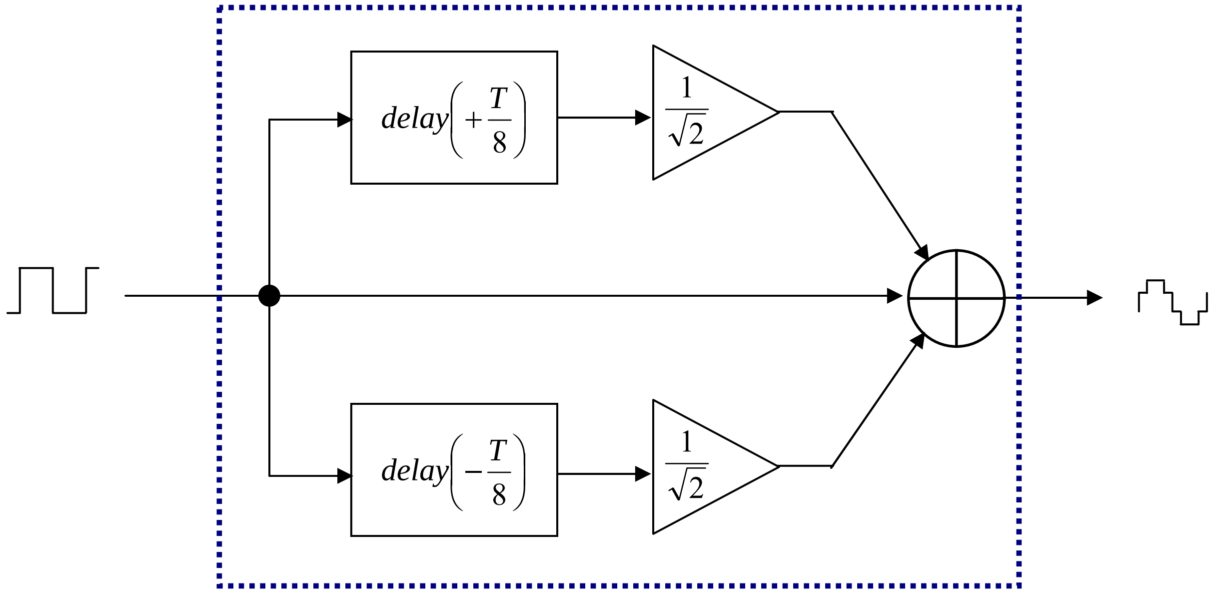


➢ Multilevel comparator



➢ Conventional comparator + Filter

❑ Filter *H*



$$H(\omega) = \left(1 + \frac{1}{\sqrt{2}} e^{-j\omega\frac{T}{8}} + \frac{1}{\sqrt{2}} e^{+j\omega\frac{T}{8}}\right)$$

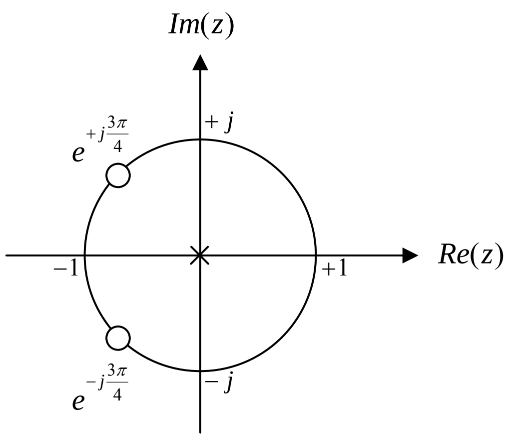
❑ Multi-level Square Wave in Discrete-time

If $T_S = T/8, \ (\omega_S = 8\omega_0)$

$$f(n) = \sqrt{2} f_S(nT_S) + f_S((n-1)T_S) + f_S((n+1)T_S)$$

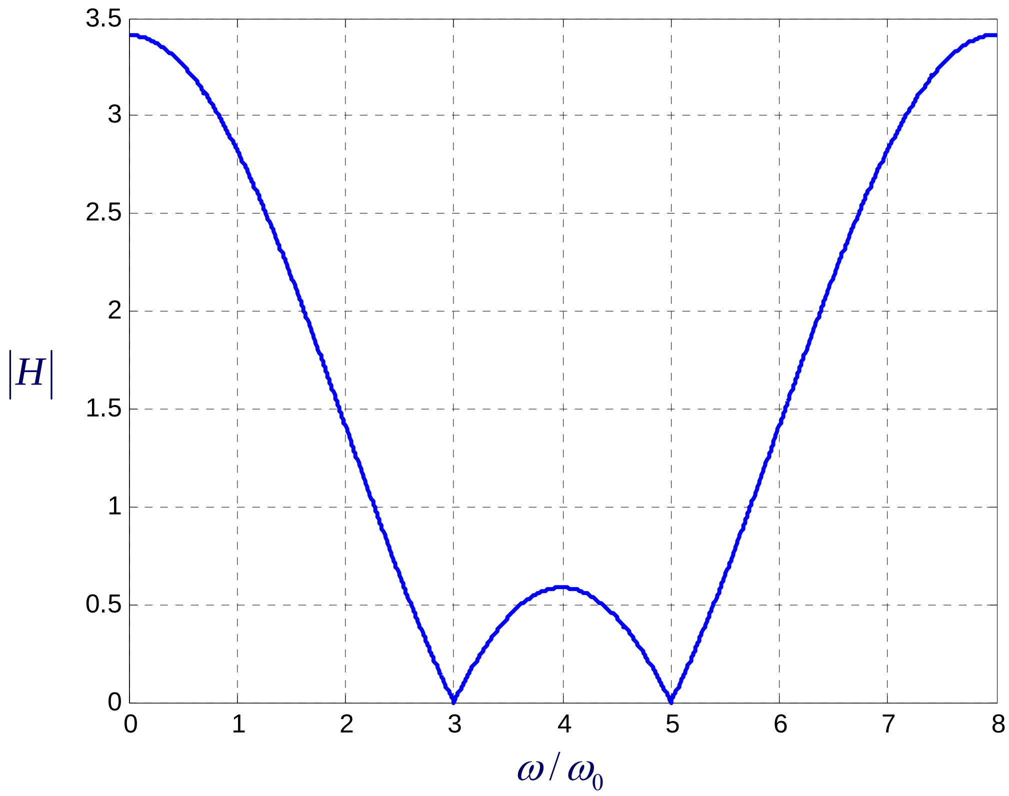
$$F(z) = z(1 + \sqrt{2}z^{-1} + z^{-2})F_S(z) = H(z)F_S(z)$$

$$H(z) = z^{-1}(z^2 + \sqrt{2}z + 1)$$



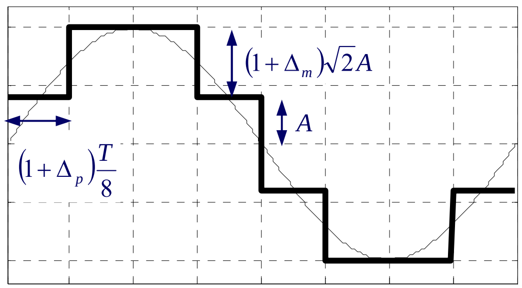
- Two zero's on the unit circle
- By sampling theorem, $\pi \Rightarrow \omega_s/2 = 4\omega_0 \quad 3\pi/4 \Rightarrow 3\omega_0 \quad -3\pi/4 \Rightarrow -3\omega_0 \ (= 5\omega_0)$
- Zero's are repeated at every $8\omega_0$

❑ Magnitude Response of 4-level Comparator

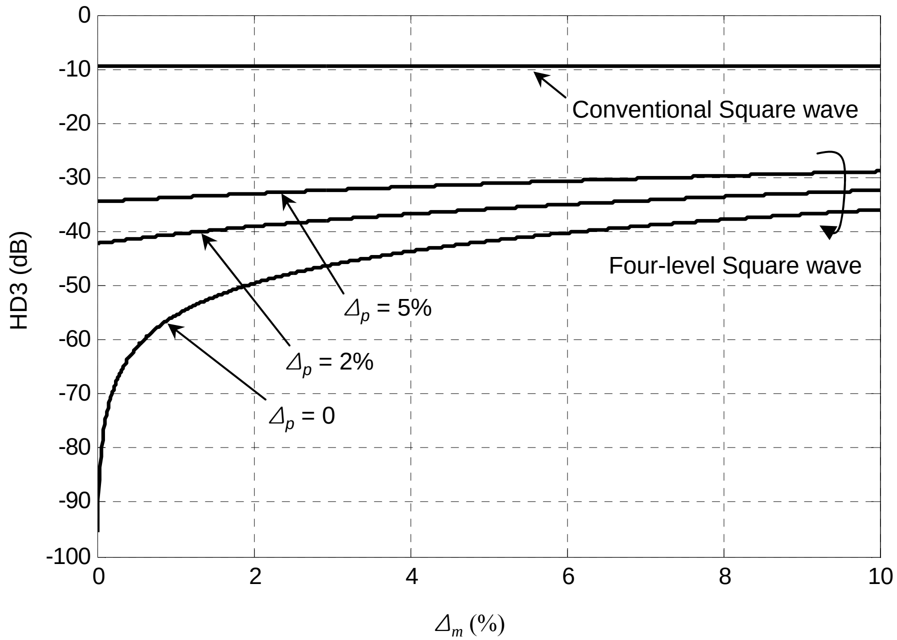


- Two zero's at $3\omega_0$ and $5\omega_0$
- [$4\omega_0$, $8\omega_0$] : Aliased from [0 , $4\omega_0$]

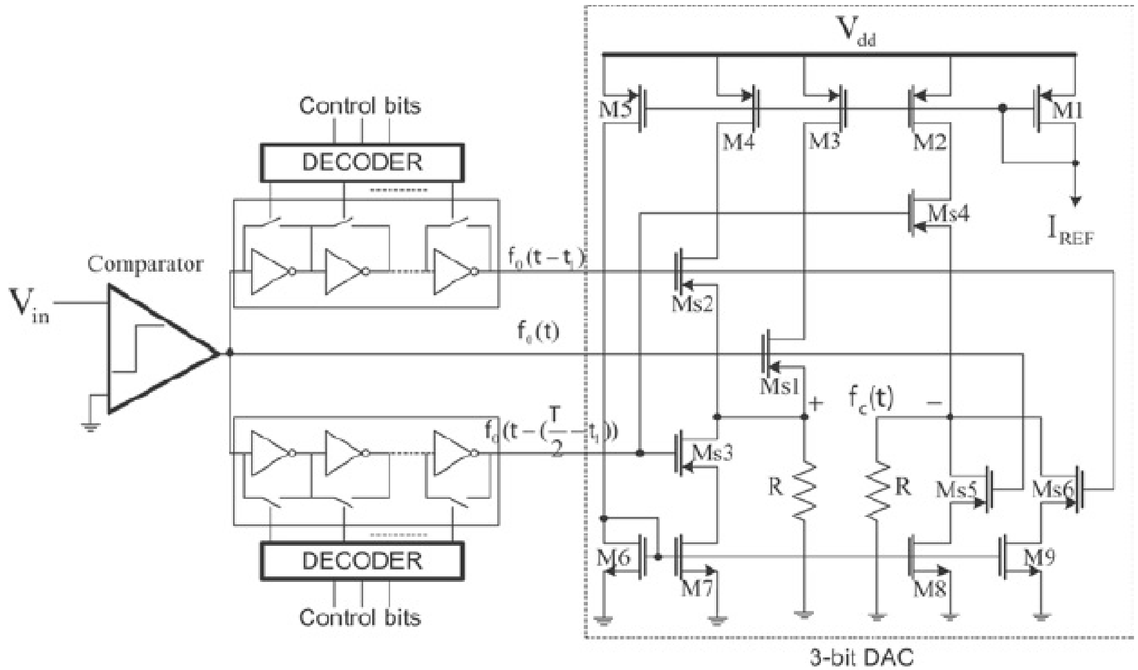
❑ Non-Ideal Effects



$$HD3 = \frac{|F(3\omega_0)|}{|F(\omega_0)|} = \frac{1}{3}\frac{|H(3\omega_0)|}{|H(\omega_0)|} = \frac{1}{3}\frac{\left|1+\sqrt{2}(1+\Delta_m)\cos\left(\frac{3\pi}{4}(1+\Delta_p)\right)\right|}{\left|1+\sqrt{2}(1+\Delta_m)\cos\left(\frac{\pi}{4}(1+\Delta_p)\right)\right|}$$



❑ BPF-based Oscillator Implementation [1]

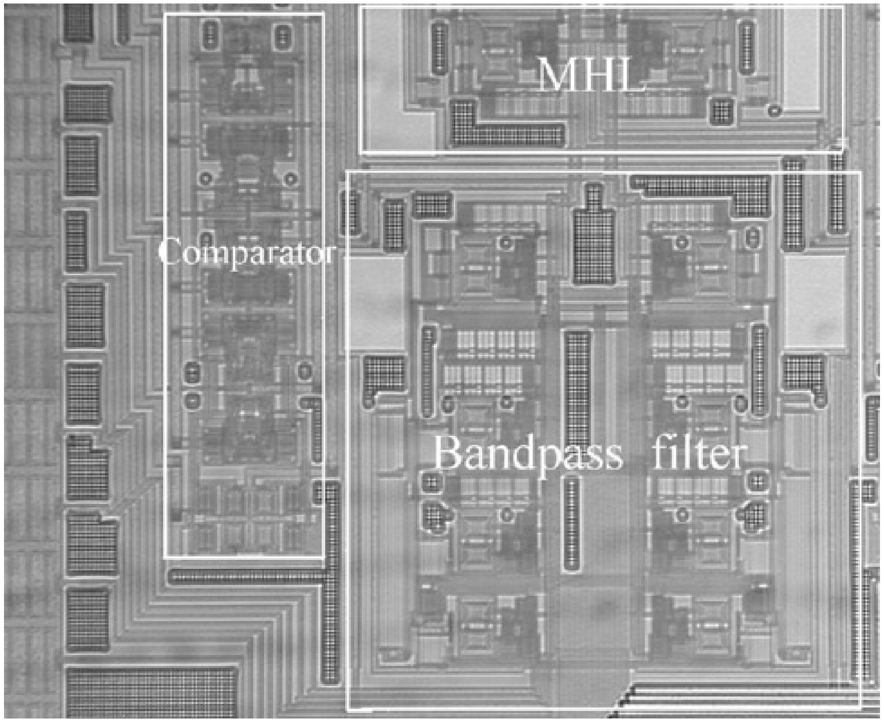


- Use one comparator
- Delay blocks for generating additional square waves
- Three square waves are combined using 3-bit DAC

[1] F.Bahmani, and E. Sánchez-Sinencio, "Low THD Bandpass-based Oscillator Using Multilevel Hard Limiter", IET Circuits, Devices & Systems, Vol. 1, No. 2, pp. 151-160, Apr. 2007

❑ BPF-based Oscillator Implementation [1]

- TSMC 0.35um process
- Power supply : ±1.5V
- Area : 3.15 mm^2
- Power consumption : 132 mW



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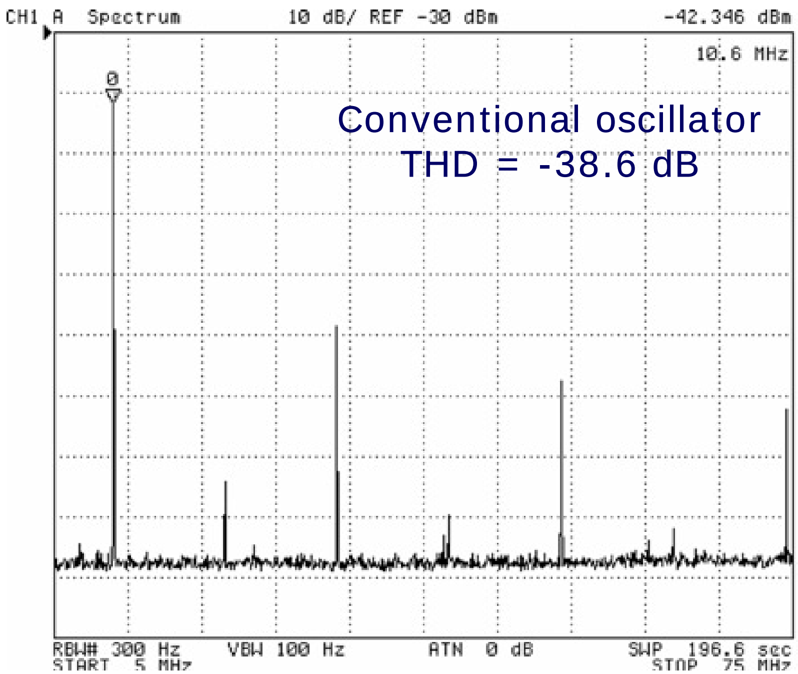
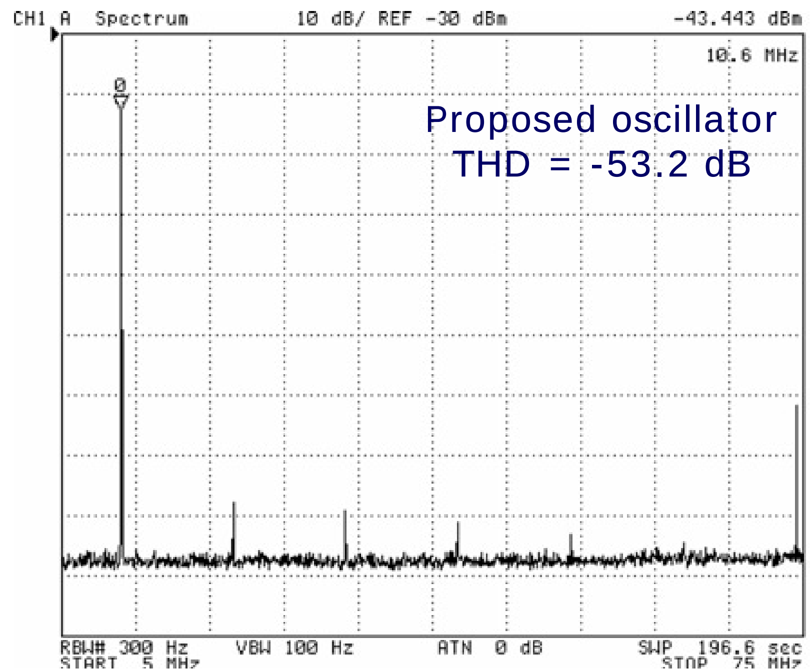
❑ BPF-based Oscillator Implementation [1]

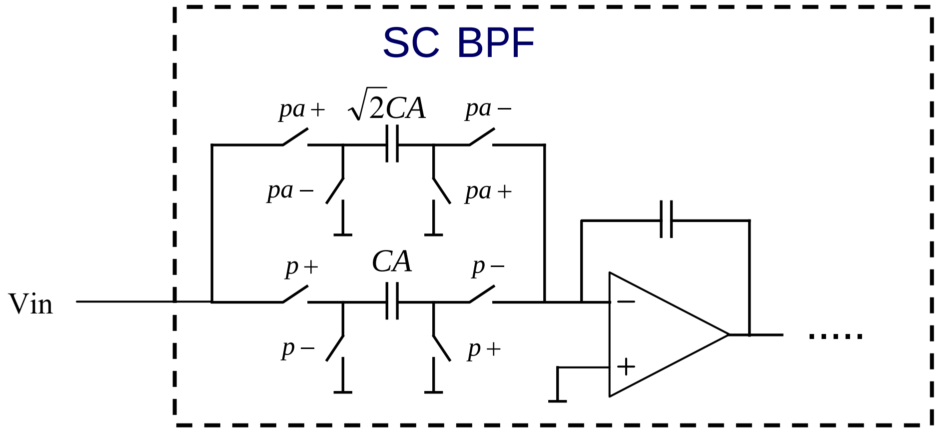


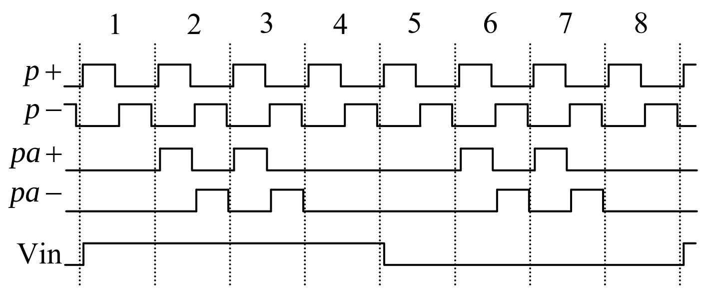


- ➢ Proposed oscillator has improved linearity by 15 dB over conventional oscillator

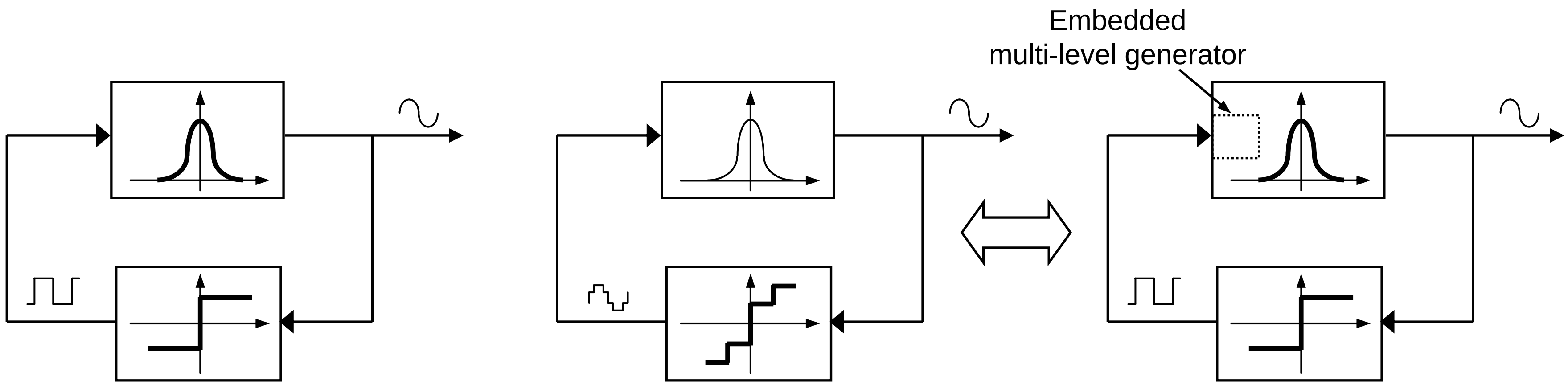
[1] F.Bahmani, and E. Sánchez-Sinencio, "Low THD Bandpass-based Oscillator Using Multilevel Hard Limiter", IET Circuits, Devices & Systems, Vol. 1, No. 2, pp. 151-160, Apr. 2007

❑ Multi-level Comparator + SC BPF





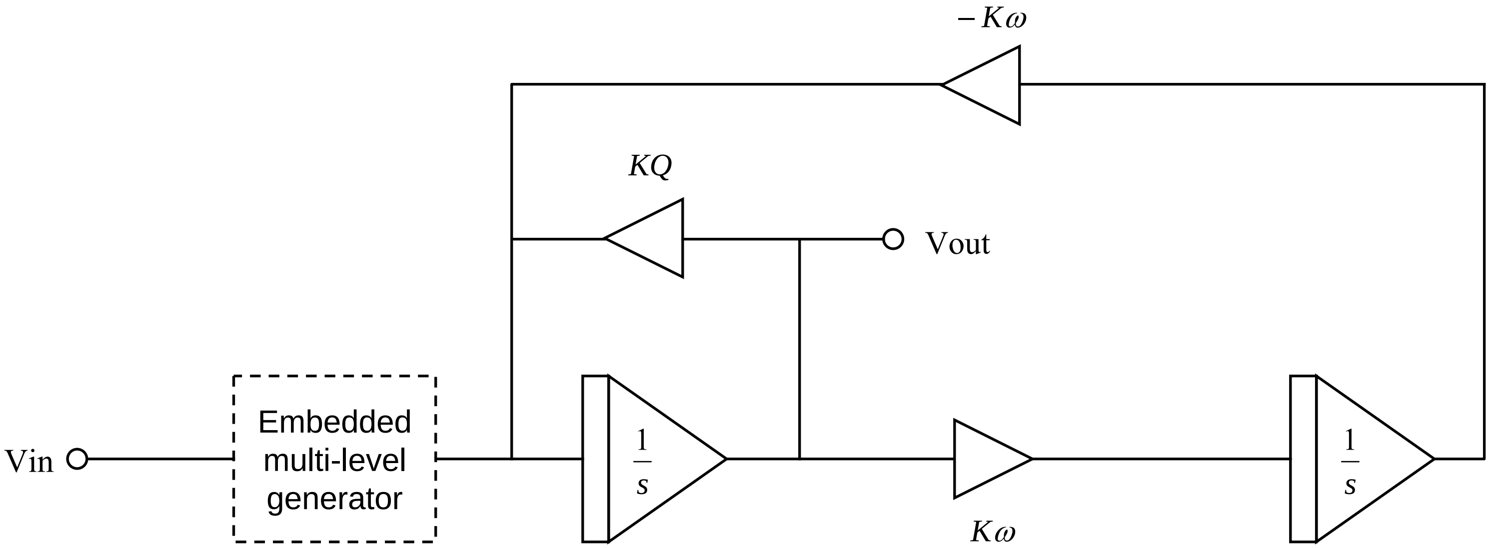
❑ SC BPF-based Oscillator



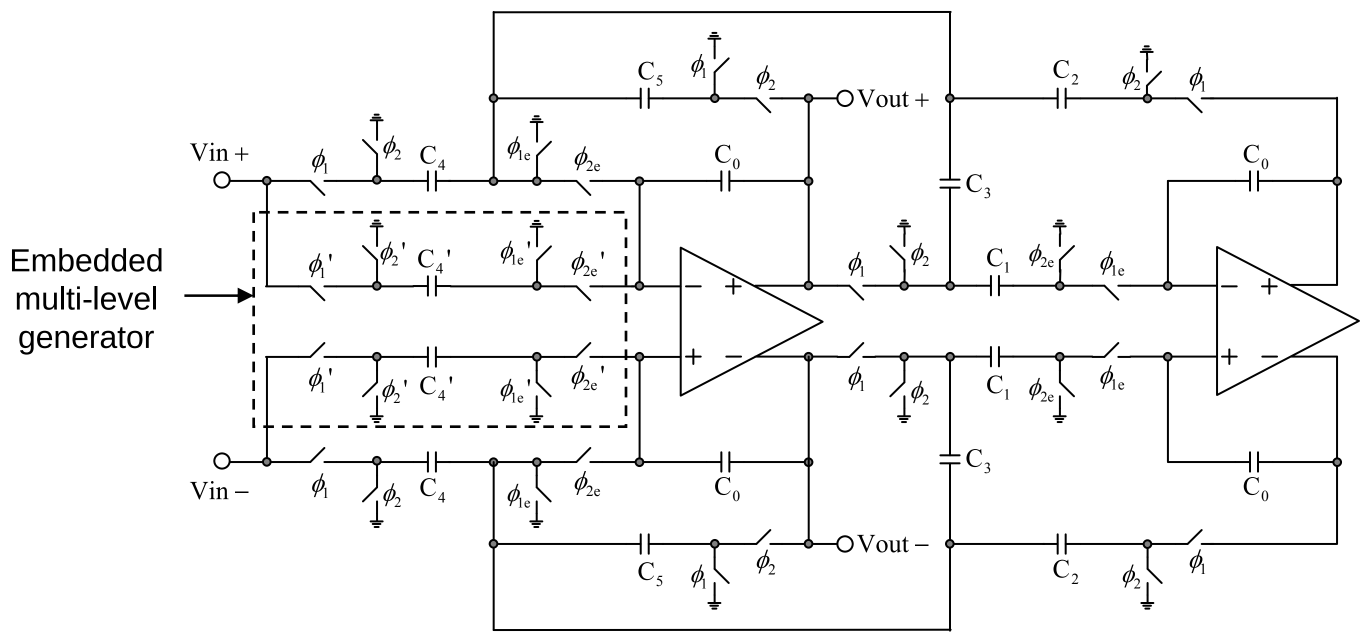
Conventional SC Oscillator | SC Oscillator with multi-level comparator | Proposed SC Oscillator

- Multi-level comparator is embedded in BPF
- Equivalent multi-level square wave

❑ SC Biquad BPF with multi-level generator

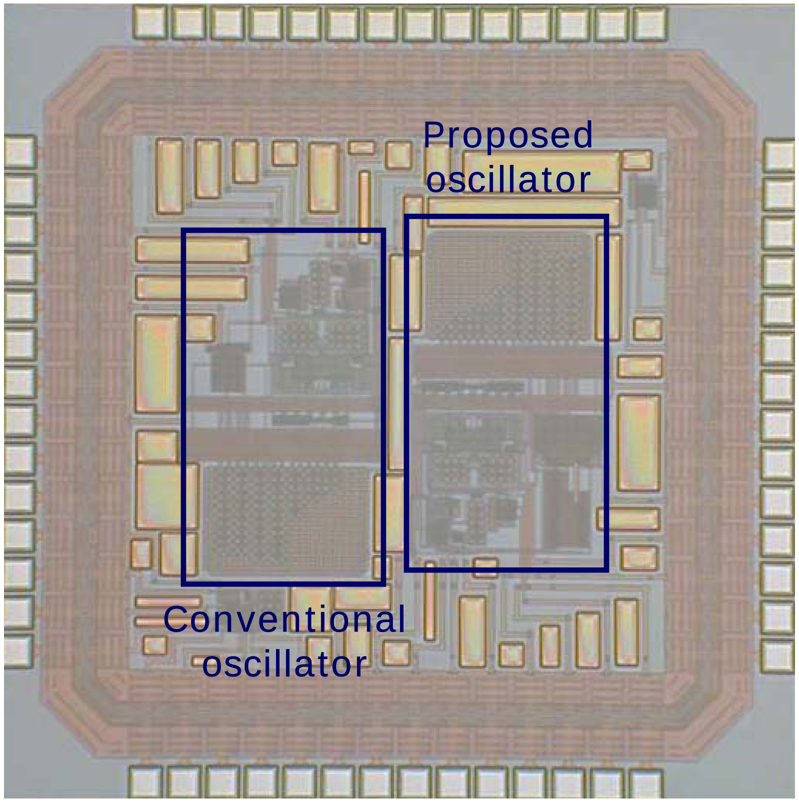


❑ SC Biquad BPF with multi-level generator



❑ SC BPF-Based Oscillator Design [2]

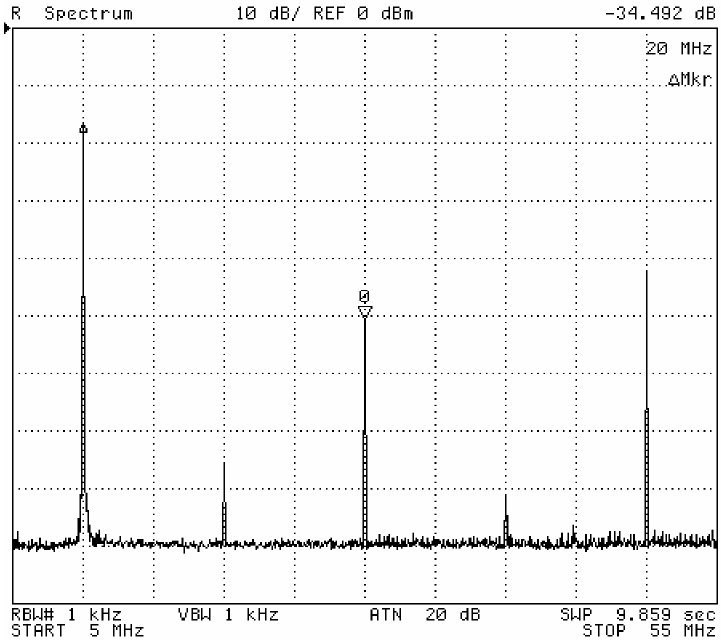
- TSMC 0.35um process
- Power supply : ±1.65V
- Area : 700um x 400um
- Power consumption :
  - 19.8 mW (Conventional)
  - 20.1 mW (Proposed)
- f_0 is tuned by clock (f_{CLK} / f_0 = 8)
- Output amplitude : 200 mV_{p-p}



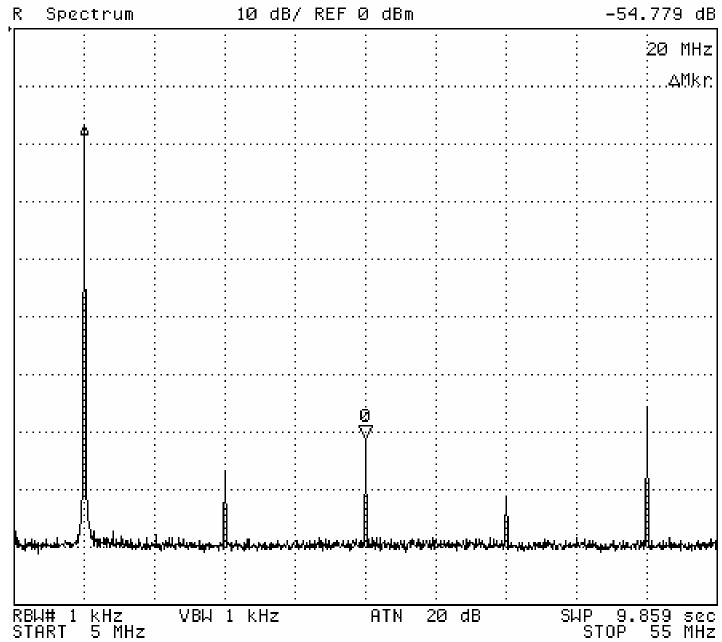
[2] Sang Wook Park, José L. Ausín, Faramarz Bahmani and Edgar Sánchez-Sinencio, "Nonlinear Shaping SC Oscillator with Enhanced Linearity", *IEEE Journal of Solid-State Circuits*, Nov, 2007

❑ SC BPF-Based Oscillator Test result

Conventional SC Oscillator
(HD3 = -34.5 dB)



Proposed SC Oscillator
(HD3 = -54.8 dB)



➢ Proposed oscillator has improved linearity by 20 dB over conventional oscillator

[2] Sang Wook Park, José L. Ausín, Faramarz Bahmani and Edgar Sánchez-Sinencio, "Nonlinear Shaping SC Oscillator with Enhanced Linearity", *IEEE Journal of Solid-State Circuits*, Nov, 2007

❑ Result Comparison

Reported	f_0	HD3	Power	Technology
J. L. Huertas, IEEE TCAS,1984	15.7 KHz	-47 dB	N/A	N/A
P. E. Fleischer, IEEE JSCC, 1985	N/A	-39 dB	N/A	3.5um CMOS
J. A. Lima, IEEE ISCAS, 2002	1.12 MHz	-41 dB* @ 321mV$_{p-p}$	0.35 mW	N/A
M. G. Mendez, J. of Electronic Testing, 2005	0.01 MHz	-38 dB @ 1V$_{p-p}$	0.05 mW	0.5um CMOS
This work (Conventional)	10 MHz	-35 dB @ 200mV$_{p-p}$	19.8 mW	0.35um CMOS
This work	10 MHz	-55 dB @ 200mV$_{p-p}$	20.1 mW	0.35um CMOS

* T.H.D.

CONCLUSION

- SC BPF-based oscillator was designed.
- Mutilevel comparator selectively rejects harmonics.
- Proposed oscillator improved HD3 by 20 dB.